CYGNO- A 3D OPTICAL READOUT TPC FOR DIRECTIONAL DARK MATTER SEARCHES

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Outline

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• How can we explore Dark Matter?
• Importance of Directionality in Dark Matter Searches
• Time Projection Chambers with Optical Readout
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• MANGO
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• LIME
• CYGNO 1m3
• What can we do?
• CYGNUS Collaboration
Dark Matter and WIMPs

- One of possible constituents of Dark Matter are the Weakly Interacting Massive Particles: neutral particles with a very low interaction probability with ordinary matter;

- Our Milky Way, like most galaxies, is surrounded by an approximately spherical halo of WIMPs. The Sun and the planets move through this halo towards CYGNUS constellation intercepting a WIMP wind originating from it.

- Events caused by Dark Matter interactions have a preferential direction in space because of the Earth’s motion with respect to the Dark Matter Halo
How can we explore Dark Matter?

- One possibility is trying to detect the products of its interactions with ordinary matter, through charged particles that we know how to detect;

- In order to maximize the fraction of transferred energy it is then crucial to have a target of almost same mass

<table>
<thead>
<tr>
<th>Element</th>
<th>Max E transferred by a 1 GeV WIMP</th>
<th>Min WIMP mass with 1 keV threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>2.00 keV</td>
<td>0.5 GeV</td>
</tr>
<tr>
<td>He</td>
<td>1.30 keV</td>
<td>0.9 GeV</td>
</tr>
<tr>
<td>C</td>
<td>0.57 keV</td>
<td>1.4 GeV</td>
</tr>
<tr>
<td>F</td>
<td>0.38 keV</td>
<td>1.7 GeV</td>
</tr>
<tr>
<td>Na</td>
<td>0.32 keV</td>
<td>1.8 GeV</td>
</tr>
<tr>
<td>Si</td>
<td>0.27 keV</td>
<td>2.0 GeV</td>
</tr>
<tr>
<td>Ar</td>
<td>0.20 keV</td>
<td>2.4 GeV</td>
</tr>
<tr>
<td>Xe</td>
<td>0.06 keV</td>
<td>4.2 GeV</td>
</tr>
</tbody>
</table>

- Large regions of high masses spectrum already explored without any confirmed evidence of WIMP
- Focus shift towards lower masses (below 10 GeV)
- Lower mass elements provide the best candidate targets (He and H)
- Enables the identification of the topological signature of different events (e.g. ER and NR)
Importance of Directionality in Dark Matter Searches

Energy information
- Falling exponential with no peculiar features

Temporal information
- A few percent (%) annual modulation

Directional information
- Allows unequivocally the identification of the event

What can we explore?
- Capability to reject isotropy
- Capability to discriminate neutrinos from WIMPs
- Capability to probe DM nature

How can we do it?
TPC with Optical Readout

What can we get?

- 3D tracking (position and direction)
- Particle ID (dE/dx)
- Axial directionality
- Head/tail
- Background rejection
- 3D fiducialization

What is our idea?

- Readout the light produced during the charge avalanche

Different technologies can be used to readout the signal.

Enabling to reduce the number of channel numbers thus the DAQ complexity.
TPC with Optical Readout

Why using optical readout?

- Readout the light produced during the charge avalanche

Optical sensors provide high sensitivity and granularity, with a fast response with very low noise level.

Optocoupling enables to keep sensor out of sensitive volume (HV independent and lower gas contamination).

Suitable lens allow the development of large sensitive area solutions.

Complete analysis of the emission spectra
CYGNO Roadmap

Phase 0: R&D

  - 1 cm drift

- LEMON: 2017–2018
  - 3D printing
  - 20 cm drift

- MANGO: 2019–2021
  - variable drift distance
  - performance testing

- LIME: 2021–2022
  - 50 cm drift
  - underground tests
  - shielding
  - data taking

- Construction & Test: 2022–2023
  - background
  - material tests
  - gas purification
  - scalability

- Installation & commissioning: 2023
  - installation and data taking with O(1) m³ detector

Phase 1: O(1) m³ Demonstrator

- CYGNUS 30–100 m³
Electroluminescence in

MANGO

First observation of EL in He-CF4 mixture
95% collection efficiency for Drift Field of 0.75 kV/cm

Measured Diffusion coefficient in agreement with Garfield expectations

\[ D_T = \frac{135 \mu m}{\sqrt{cm}} \]

500 photons collected per keV

Sensor noise below 200 photons (i.e. 400 eV)

Energy resolution of 15% at 5.9 keV from both sCMOS and PMT

Diffusion can be explored to evaluate the Z position with an average resolution of 15%.

Transverse light profile and PMT signal waveform are expected to become smaller and larger.

Since the width (S) increases and the amplitude (A) decreases with Z, their ratio increases.
Performance assessment with 450 MeV electrons

Diffusion can be explored to evaluate the Z position with an average resolution of 15%.

\[ \sigma = \sqrt{\sigma_0^2 + \sigma_Z^2} \]

\[ \sigma_0 = 292 \pm 12 \text{ \( \mu \)m} \]

(electron avalanche contribution)

\[ \sigma_Z = mZ + q \]

\[ m = 10.9 \pm 1.0 \]

\[ q = 83 \pm 12 \]
Performance assessment - Capability of identifying low-energy NR and discrimination capability (NR/ER)

A sizeable efficiency in the range 5-10 keV was measured while more than 95% (99%) 55Fe photons were rejected.
LIME

Large sensitivity
Low noise

ORCA-fusion

Large sensitivity
Low noise
LIME is expected to be installed underground at LNGS (3600 m.w.e.) by fall 2021.

LIME goals:

- Measure environmental neutron flux
- Measure internal backgrounds towards O (1) m3 detector development

Gamma Shielding (10 cm Cu)

Neutron Shielding (50 cm water)
Preliminary CYGNO $O(1)\,m^3$

- $O(1)\,m^3$ of He-CF$_4$ (60-40) at atmospheric pressure and room temperature
- Modular detector - LIME-like modules
- Back-to-back TPC with 50 cm drift of 1 kV/cm

Amplification Stage made using a triple-GEM

Central cathode

GEM (~1x1 m$^2$)

Acrylic vessel

Radioactivity shielding:
- 5 cm thick copper box (and similar Faraday cage)
- 200 cm of water

sCMOS sensor 65 cm away
Almost $10^8$ readout pixels (165x165 um$^2$)

Fast light detector (PMT or SiPM).
What opportunities are there?

Neutrinos are seen as unwanted background but can also be interesting to explore.

**Neutrino Spectroscopy**

Using a gaseous TPC we can study the neutrinos via electron scattering.

**Here is the reason why...**

- sub-millimetre tracking capability (Borexino is 12 cm)
- 10 keV directional threshold for electron recoils
- keV energy resolution
- low mass target

**For 1 m$^3$ of He:CF$_4$ 60:40 with 20 keV threshold**

\[
R = N_e \int_{E_{\text{min}}}^{E_{\text{max}}} w(E) \varphi_{\text{pp}}(E) \sigma(E) dE
\]

\[
R = 2.9 \cdot 10^{-8} \quad \text{events} \quad \frac{\text{s}}{\text{m}^3} = 0.9 \quad \text{events} \quad \frac{\text{y}}{\text{m}^3}
\]

Given the Sun position, recoils in opposite direction are kinematically forbidden.
CYGNUS Collaboration

CYGNO project is developing a GEM-based TPC optically readout for rare event studies. Very promising performance was found in the keV region.

CYGNUS is working in the framework of CYGNUS: an international Collaboration aiming at the realisation of Multi-site Recoil Directional Observatory for WIMPs and neutrinos.

More than 50 signed members UK, Japan, Italy, Spain, China focused on gas TPCs with 2D or 3D direction sensitivity;
Thank you
Acknowledgements

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Backup slides
Why sCMOS and PMTs?

- High granularity
- Lower number of channels to readout large areas
- X-Y position and energy deposit measurements
- Fast response

1/3 noise w.r.t. CCDs
Market pulled
Single photon sensitivity
Decoupled from target gas
Large areas with proper optics

A.F.V. Cortez, CYGNO – A 3D Optical Readout TPC for Directional Dark Matter Searches, 16th PATRAS Workshop on Axions, WIMPS and WISPs, 14-18 June 2021

He nuclear recoil

Soft electron from natural radioactivity

450 MeV electron with its δ ray